

MASSIVE STAR FORMATION OF THE SGR A EAST H II REGIONS NEAR THE GALACTIC CENTER

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ABSTRACT

A group of four compact H II regions associated with the well-known 50 km s⁻¹ molecular cloud is the closest site of on-going star formation to the dynamical center of the Galaxy, at a projected distance of \sim 6 pc. We present a study of ionized gas based on the [Ne II] (12.8 μ m) line, as well as multi-frequency radio continuum, *Hubble Space Telescope Pa α* , and *Spitzer* Infrared Array Camera observations of the most compact member of the H II group, Sgr A East H II D. The radio continuum image at 6 cm shows that this source breaks up into two equally bright ionized features, D1 and D2. The spectral energy distribution of the D source is consistent with it being due to a $25 \pm 3 M_{\odot}$ star with a luminosity of $8 \pm 3 \times 10^4 L_{\odot}$. The inferred mass, effective temperature of the UV source, and the ionization rate are compatible with a young O9-B0 star. The ionized features D1 and D2 are considered to be ionized by UV radiation collimated by an accretion disk. We consider that the central massive star photoevaporates its circumstellar disk on a timescale of 3×10^4 years giving a mass flux $\sim 3 \times 10^{-5} M_{\odot}$ yr⁻¹ and producing the ionized material in D1 and D2 expanding in an inhomogeneous medium. The ionized gas kinematics, as traced by the [Ne II] emission, is difficult to interpret, but it could be explained by the interaction of a bipolar jet with surrounding gas along with what appears to be a conical wall of lower velocity gas. The other H II regions, Sgr A East A-C, have morphologies and kinematics that more closely resemble cometary flows seen in other compact H II regions, where gas moves along a paraboloidal surface formed by the interaction of a stellar wind with a molecular cloud.

Key words: Galaxy: center – H II regions – stars: early-type

1. INTRODUCTION

The Galactic center region is known to have a high concentration of massive, warm, dense, and turbulent molecular clouds. Due to strong tidal forces exerted by the gravitational potential of the nuclear cluster and the massive black hole, Sgr A*, only dense molecular gas is expected to survive in this region (see Morris & Serabyn 1996). This has the ramification that the formation of massive stellar clusters must be pervasive in this region, as evidenced by the Arches and Quintuplet clusters as well as the nuclear massive cluster centered on Sgr A* (Figer et al. 2002; Bartko et al. 2009, and references therein). There are also young clusters of O-B stars traced by ultracompact (UC) H II regions in Sgr B2 (e.g., DePree et al. 1998) which is possibly the best example of mini-starburst activity in the Galaxy. Although our present understanding of star formation is primarily limited to observations of low-mass stars (Shu et al. 1987; McKee & Ostriker 2007; Zinnecker & Yorke 2007), probing star-forming sites in the Galactic center region can be useful in addressing the key mechanism by which massive stars are formed ($M > 10 M_{\odot}$; see Hoare et al. 2007, and references cited therein).

Here, we examine the nature of a group of massive young stars lying within 2.5' of the dynamical center of the Galaxy (Reid & Brunthaler 2004; Ghez et al. 2008; Gillessen et al. 2009). At a projected distance of 6 pc from Sgr A*, there is a cluster of compact H II regions on the edge of the 50 km s⁻¹

molecular cloud M-0.02–0.07. This cluster consists of brightest H II regions in the Galactic center with the exception of the cluster of H II regions in Sgr B2. The 50 km s⁻¹ molecular cloud itself is interacting with the nonthermal Sgr A East (e.g., Tsuboi et al. 2009, and references cited therein) which is known to be a supernova remnant (SNR G0.0+0.0). Since Sgr A East appears to be interacting with the Galactic center circumnuclear molecular ring, which itself orbits Sgr A*, it is probable that Sgr A East, M-0.02–0.07, and the cluster of H II regions all lie near the Galactic center, not far from their projected distances. The compact H II regions, known as the Sgr A East H II A–D (Sgr A A–D), trace the site of recent massive star formation nearest to the dynamical center of the Galaxy. The four H II regions have radial velocities ranging between 43 and 49 km s⁻¹, and thus appear dynamically coupled to the 50 km s⁻¹ molecular cloud (Goss et al. 1985; Serabyn et al. 1992). With the exception of [Ar III] emission from Sgr A–D H II source, IR spectroscopic measurements detected [Ne II] and [Ar III] line emission from all four components (A–D), indicating that the exciting stars have spectral types of O8–B0 (Serabyn et al. 1992), consistent with H76 α measurements (Goss et al. 1985).

The measured extinction toward Sgr A East A–C is less than that of source D (Cotera et al. 1999; Serabyn et al. 1992). Additional extinction for source D is likely due to the 50 km s⁻¹ molecular clouds or due to material associated with the ionizing stellar source (Serabyn et al. 1992). These authors estimate that the extinction values at 12.8 μ m are \sim 1–1.3 mag for A–C and \sim 3.3 toward the Sgr A D source. These extinction measurements imply that the Sgr A East A–C H II regions, which are resolved spatially, are located on the front side of the molecular cloud, whereas the compact Sgr A D source

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mass above $0.5 M_{\odot}$ of $940 M_{\odot}$ associated with a group of young stars in Sgr A East. Assuming that the typical age of the cluster is $\sim 10^5$ – 10^6 years, we estimate a star formation rate of 0.01 – $0.001 M_{\odot} \text{ yr}^{-1}$. We can also make an estimate of the total mass of molecular gas that went into forming stars. We used the $850 \mu\text{m}$ images of Figure 1 to estimate the depleted gas mass by converting submillimeter flux to the mass of molecular gas. We estimate a subtracted flux of 15 Jy at $850 \mu\text{m}$ depleted from the region where the group of H II regions is distributed. We assumed that dust emission from the 50 km s^{-1} cloud was uniformly distributed inside and outside the H II regions prior the formation of stars. For a dust temperature of 20 K and a conversion factor from $850 \mu\text{m}$ to gas mass (Pierce-Price et al. 2000), we find a rough total gas mass of $7.7 \times 10^3 M_{\odot}$ that dissipated and converted into $940 M_{\odot}$ of stars.

The near-infrared observations show that despite the ionized gas morphology suggesting a pair of compact H II region, it is probably a single source that is exciting both D1 and D2. Presumably D1 is produced by irradiation of a dense clump of gas distributed within a cavity that has been partly evacuated of lower density gas by the stellar radiation field. In this scenario, the clump has an angular diameter of $\sim 8000 \text{ AU}$ and lies at a projected distance of $\sim 12000 \text{ AU}$ from D2, and so intercepts approximately 10% of the ionizing photons escaping the D1 region. The observed 30 mJy flux at 43 GHz requires a total ionization rate at the clump surface of $\sim 2 \times 10^{47} \text{ s}^{-1}$, implying that the exciting source is emitting ionizing photons at a rate $\sim 2 \times 10^{48} \text{ s}^{-1}$.

4.2. The Kinematics of Source D

We now attempt to construct a model to explain the observations of source D. In particular, we need to explain the spatial distribution of the ionized gas and infrared continuum emission, as well as the motions of the ionized gas.

The ionized gas is distributed between two sources, D1 and D2, each of which is elongated in the NS direction. It is nearly symmetric about a NS line passing between D1 and D2, but with the eastern peak, D1, lying somewhat north of the western peak, D2, with a P.A. $\sim 70^\circ$. The infrared continuum, at both $1.9 \mu\text{m}$ and $12.8 \mu\text{m}$, shows a single peak that lies between the ionized gas peaks, but probably closer to D2. The kinematics of the ionized gas can be described by two probably related structures. A pair of spectrally broad features extend to the north from the D1 and D2 peaks. The eastern feature extends in velocity from near the molecular cloud velocity redward by about 30 km s^{-1} . The western feature extends about 30 km s^{-1} blueward of the molecular cloud. Lower velocity emission is seen both north and south of the peaks, broadening both spectrally and spatially going to the north.

The two broad-lined emission features seem most naturally explained by a bipolar jet pair, probably interacting with the wall of a cavity. The jet could originate from a young star surrounded by a disk, lying between D1 and D2. The disk axis is tipped at a P.A. $\approx 70^\circ$, with the west side tipped toward us, so that the western jet is blueshifted. The fact that the jets are not seen extending to the east and west of D1 and D2 indicates that the observed [Ne II] emission is not from the jets themselves, but from the region of interaction between the jets and a surrounding wall. In fact, the bright emission peaks could be simply regions of a wall which are illuminated by ionizing radiation, but the width of the emission lines indicates that jets are needed. The offset between the position of the $1.9 \mu\text{m}$ continuum and the position of the axis of the symmetry of D1/D2 can also be

explained by inhomogeneity of gaseous material in the vicinity of the star and/or the motion of the star. Figure 9 shows a schematic diagram of the relative location of D1, D2, and the central massive star with a flaring disk. The fact that D1 is redshifted and D2 is blueshifted could be explained if the disk is seen at an angle between edge-on and face-on, with the west side of the disk tipped toward us. The lack of symmetry in this diagram is likely the result of density gradient surrounding the star. The 50 km s^{-1} molecular cloud lies mainly to the west of the central star.

High-mass stars efficiently photoevaporate their circumstellar disks on timescales of 10^4 – 10^5 years. The piling up of the resulting disk wind as it expands against the surrounding medium could be responsible for the $\sim 0.1 M_{\odot}$ of ionized material we identify as sources D1 and D2. The semianalytic photoevaporated disk-wind model of Hollenbach et al. (1994) applied to a $28 M_{\odot}$ star yields a mass flux $\sim 3 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$, indicating an age of $\sim 3 \times 10^4$ years. The momentum of the material would be maintained by contributions from the momentum fluxes $Mv \sim 3 \times 10^{-4} M_{\odot} \text{ km s}^{-1}$ from each of the disk wind ($v \gtrsim 10 \text{ km s}^{-1}$; Drew et al. 1998; Hoare 2006) and stellar wind ($\sim 3 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ and $v \sim 1000 \text{ km s}^{-1}$). Another potential contribution could arise from a fraction of the total momentum flux $10^5 L_{\odot}/c \sim 1 \times 10^{28} \sim 2 \times 10^{-3} M_{\odot} \text{ yr}^{-1} \text{ km s}^{-1}$ in the photons emitted by the central star.

The extensions to the north could trace the regions of interaction of the jets with the cavity wall if the star is moving to the south, although it is not apparent why broad-lined emission would persist after the jets pass by. An explanation is also needed for the probable offset of the infrared continuum emission toward D2. One possibility is that the disk that collimates the jets is close enough to edge-on that it prevents a direct view of the central star even in the infrared. The near infrared continuum radiation could be scattered into our line of sight by the material that forms the ionized gas peak D2. Since D1 lies on the far side of the disk, backscattering (which would be less efficient) would be required for it D1 to be seen in scattered light. It may also be obscured by the disk if the disk extends out far enough to cover it. The $12.8 \mu\text{m}$ continuum is unlikely to be scattered, but it could also be affected by extinction, and it is not so convincingly offset from the center of D as is the $1.9 \mu\text{m}$ emission.

The spectrally narrow emission extending both north and south of the D peaks is even more difficult to explain than the broad-lined emission. The ring-like pattern seen in the PV diagrams in Figure 7 could be due to gas in each cut lying on an expanding ring. The fact that the PV rings increase in spatial and velocity extent going to the north would indicate that the three-dimensional ionized gas distribution is on the surface of an expanding cone, with the expansion speed increasing to the north. Alternatively, the gas could be flowing along the surface of a cone if it is accelerating so as to make its speed increase linearly with declination. However, we cannot propose a physical model that would cause either of these flow patterns. We know of no other case of an expanding cone like what we suggest or any reason a conical wall would expand in this way. A flow along the surface of a cone seems more natural, but all cometary H II regions we have observed, with sources A–C being representative, are paraboloidal rather than conical, with much larger opening angles than in D. They also have most of their acceleration in a small distance from their vertexes. (A constant dv/dt would result in $v^2 \propto r$, or $dv/dr \propto r^{-1/2}$, rather than

the observed constant dv/dr .) It is especially puzzling that the ionized cone has its vertex 3'' south of D, so presumably leading the ionizing star, which we think is moving in that direction. We have to conclude that we are unable to propose a consistent model for the NS velocity of ionized gas associated with source D. The narrow-lined gas appears to be distributed on the surface of a wedge or cone with an opening angle $\sim 20^\circ$, with its vertex $\sim 3''$ south of the star.

4.3. The Kinematics of Source A

Why are cometary H II sources A–C oriented head-on, with velocity offsets indicating that their ionizing stars are moving through the 50 km s $^{-1}$ molecular cloud, whereas most cometary H II regions seen in [Ne II] are seen tail-on with little stellar motion? The answer may lie in the circumstances of their formation. The location of the Sgr A East H II regions near the edge of the Sgr A East SNR suggests that the ionizing stars may have formed as a result of compression of molecular gas by the SNR. If the stars formed in swept-up gas, they would have formed with the velocity of the gas. After their formation, the compressed shell would have slowed as more gas was swept up, and the stars could have drifted out of the compressed gas. The stars may now be moving through gas of low enough density that extinction does not affect the [Ne II] emission, as it would if they were still inside of a dense molecular cloud. From the orientation of its broken shell, it appears that the ionizing star of H II source A is moving to the east, as well as toward us. From the offset of its PV diagram, its motion relative to the 50 km s $^{-1}$ molecular cloud is ~ 30 km s $^{-1}$. The ionizing stars of sources B and C have similar motions. In particular, the PV diagrams indicate that all three sources are moving toward us, while source B is moving to the east and source C is moving to the northeast.

The ~ 50 km s $^{-1}$ velocity width of the [Ne II] line is consistent with other UC H II regions (e.g., Garay & Lizano 1999). The characterization of a cluster of H II regions Sgr A A–D may not be correct, as these H II regions appear to be unbound due to their large physical separation, signifying isolated star formation near the Galactic center. Again, the site of on-going star formation is consistent with sites of massive star formation elsewhere (e.g., Garay & Lizano 1999).

4.4. Conclusions

We thank the referee for a thorough reading of the paper and for useful comments. We have presented multi-wavelength observations of a chain of H II regions located at the eastern edge of the Sgr A East SNR and the 50 km s $^{-1}$ molecular cloud. These H II regions show the youngest star formation activity closest to the Galactic center. The youngest member of Sgr A East H II regions G359.956–0.08 or the Sgr A D source is estimated to have an age of roughly 1.5×10^4 years and consists of two elongated ionized features. We identified the central star responsible for ionizing both components of the D source. The SED fit of the central star indicates a mass of $25 M_\odot$ and a luminosity of $8 \times 10^4 L_\odot$. The kinematics of ionized gas show an E–W red- and blueshifted flow with respect to the central star and a complex asymmetric velocity structure in the N–S direction. We presented a simple model in which the central star

is surrounded by a disk constraining the flow of ionized wind. In this picture, the UV radiation from the central hot star may generate an outflow from the disk, sweeping up the interstellar medium gas and forming the two components of ionized gas D1 and D2. Given that high density molecular material is distributed to the west, the ionized feature D2 is expected to lie closer to the central star. Future high spectral resolution observations of ionized gas and detailed modeling of the complex N–S velocity structure should explain better the kinematics of ionized gas presented here.

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REFERENCES

- Arendt, R. G., et al. 2008, ApJ, 682, 384
- Arthur, S. J., & Hoare, M. G. 2006, ApJS, 165, 283
- Bartko, H., et al. 2009, ApJ, 697, 1741
- Benjamin, R. A., et al. 2003, PASP, 115, 953
- Cotera, A. S., Simpson, J. P., Erickson, E. F., Colgan, S. W. J., Burton, M. G., & Allen, D. A. 1999, ApJ, 510, 747
- dePree, C. G., Goss, W. M., & Gaume, R. A. 1998, ApJ, 500, 847
- Drew, J. E., Proga, D., & Stone, J. M. 1998, MNRAS, 296, L6
- Fey, A. L., Gaume, R. A., Claussen, M. J., & Vrba, F. J. 1995, ApJ, 453, 308
- Figer, D. F., et al. 2002, ApJ, 581, 258
- Garay, G., & Lizano, S. 1999, PASP, 111, 1049
- Ghez, A. M., et al. 2008, ApJ, 689, 1044
- Gillesen, S., Eisenhauer, F., Trippe, S., Alexander, T., Genzel, R., Martins, F., & Ott, T. 2009, ApJ, 692, 1075
- Goss, W. M., Schwarz, U. J., van Gorkom, J. H., & Ekers, R. D. 1985, MNRAS, 215, 69
- Hoare, M. G. 2006, ApJ, 649, 856
- Hoare, M. G., Kurtz, S. E., Lizano, S., Keto, E., & Hofner, P. 2007, in Protostars and Planets V, ed. B. Reipurth, D. Jewitt, & K. Keil (Tucson, AZ: Univ. Arizona Press), 181
- Hollenbach, D., Johnstone, D., Lizano, S., & Shu, F. 1994, ApJ, 428, 654
- Kroupa, P. 2001, MNRAS, 322, 231
- Lacy, J. H., Richter, M. J., Greathouse, T. K., Jaffe, D. T., & Zhu, Q. 2002, PASP, 114, 153
- McKee, C. F., & Ostriker, E. C. 2007, ARA&A, 45, 565
- Morris, M., & Serabyn, E. 1996, ARA&A, 34, 645
- Pierce-Price, D., et al. 2000, ApJ, 545, L121
- Ramirez, S. V., Arendt, R. G., Sellgren, K., Stolovy, S. R., Cotera, A., Smith, H. A., & Yusef-Zadeh, F. 2008, ApJS, 175, 147
- Reid, M. J., & Brunthaler, A. 2004, ApJ, 616, 872
- Robitaille, T. P., Whitney, B. A., Indebetouw, R., & Wood, K. 2007, ApJS, 169, 328
- Serabyn, E., Lacy, J. H., & Achtermann, J. M. 1992, ApJ, 395, 166
- Shu, F. H., Adams, F. C., & Lizano, S. 1987, ARA&A, 25, 23
- Stolovy, S., et al. 2006, J. Phys. Conf. Ser., 54, 176
- Tsuboi, M., Miyazaki, A., & Okumura, S. K. 2009, PASJ, 61, 29
- Vacca, W. D., Garmany, C. D., & Shull, J. M. 1996, ApJ, 460, 914
- Wang, Q. D., et al. 2010, MNRAS, 402, 895
- Whitney, B. A., Wood, K., Bjorkman, J. E., & Cohen, M. 2003, ApJ, 598, 1079
- Wilkin, F. P. 1996, ApJ, 459, L31
- Yusef-Zadeh, F., & Morris, M. 1987, ApJ, 320, 545
- Yusef-Zadeh, F., Telesco, C. M., & Decher, R. 1989, in IAU Symp. 136, The Center of the Galaxy, ed. Mark Morris (Dordrecht: Kluwer), 287
- Yusef-Zadeh, F., & Wardle, M. 1993, ApJ, 405, 584
- Zhu, Q.-F., Lacy, J. H., Jaffe, D. T., Richter, M. J., & Greathouse, T. K. 2008, ApJS, 177, 584
- Zinnecker, H., & Yorke, H. W. 2007, ARA&A, 45, 481

